Monitoring Coastal Marshes for Persistent Saltwater Intrusion

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Abstract-Saltwater flooding of coastal marshes by storm surge, rising sea level, and subsidence is a primary cause of wetland deterioration and habitat loss. The objective of this study is to provide resource managers with remote sensing products that support ecosystem-forecasting models requiring inundation data. This investigation employed time-series indices derived from 250-meter NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and 30-m Landsat imagery to map flooding and saltwater stress in the Sabine Basin in southwest Louisiana, before and after Hurricane Rita in 2005. After nearly 20 feet of storm surge inundated the area during Hurricane Rita, Hurricane Ike produced a storm surge of almost 14 feet in the same area and flooded areas as far as 30 miles inland. The study design of this investigation centered upon the use of vegetation and wetness (water) indicators to map flooded areas. The study team assigned a vegetation index to marsh areas of concomitant vegetation and water. We derived daily MODIS time series of Normalized Difference Vegetation Index, Normalized Difference Water Index, and Normalized Difference Soil Index from the NASA Stennis Space Center Time Series Product Tool, which provides the capability to compute phenological parameters and performs temporal modeling at ecosystem scales. We estimated the extent of flooding as the percentage of time the MODIS index was water; i.e., below a certain threshold. The percentages indicate areas of persistent flooding over certain time intervals, thereby informing planners of areas with a high probability of conversion to open water. The study team used Landsat 5 and 7 data for the years 2004 through 2006 to produce an 8-day time series of vegetation and wetness indices. We evaluated these Landsat-based flood maps with lidar data and in situ elevation data collected by the U.S. Geological Survey (USGS) and Louisiana Department of Natural Resources Coastwide Reference Monitoring System for the Sabine Basin. Finally, we combined salinity data collected in situ from the USGS and from the National Oceanic and Atmospheric Administration with our flooding estimates to map areas of persistent saltwater intrusion. The combination of these data are useful for habitat switching modules that predict the migration of marsh species from one salinity regime to another from estimates of the annual percent inundation and the mean annual salinity.

I. INTRODUCTION

The Calcasieu-Sabine Basin is located in southwestern Louisiana; the Sabine River borders Louisiana and Texas (Fig. 1). This estuary was two distinct hydrologic units previously separated by the Gum Cove Ridge, with minimal saltwater intrusion from the Gulf of Mexico. Dredging operations in the Calcasieu and Sabine Rivers increased the flow of saltwater inland from the Gulf of Mexico. The construction of the Gulf Intracoastal Waterway and other inland canals connected the two basins and allowed saline waters from the Gulf of Mexico to permeate and destabilize the freshwater equilibrium that had once existed further inland [1]. The Calcasieu-Sabine Basin became more vulnerable to storm events due to these hydrological modifications, which exposed formerly sheltered areas to the threat of saltwater inundation.

The Sabine Basin study area is expansive and covers about 312,500 acres of wetlands, consisting of 32,800 acres of fresh marsh, 112,000 acres of intermediate marsh, 158,200 acres of brackish marsh, and 9,500 acres of saline marsh. Vegetative communities must adapt to a variable salinity regime set by the rate of subsidence and local sea level rise from storm surge– factors that have the potential to exacerbate the current vulnerability as the threat of erosion and displacement by saltwater looms over larger areas of this coastal ecosystem. Therefore, monitoring the Calcasieu-Sabine Basin for persistent saltwater intrusion is important to any marsh restoration and revitalization project in the area.

II. METHODS

Several investigators [2,3] successfully employed indices derived from satellite imagery to monitor vegetation stress in marsh ecosystems due to Hurricanes Katrina and Rita in Mississippi/Louisiana and in Louisiana/Texas, respectively. The current investigation derived time series from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) combined with the spatially enhanced resolution of Landsat to identify areas in the Calcasieu-Sabine Basin that are subjected to persistent saltwater flooding. We used in situ data available from the U.S. Geological Survey's Coastwide Reference Monitoring System (CRMS) and the National Oceanic and Atmospheric Administration's National Data Buoy Center coastal and inland stations to validate all data products derived from satellite observations.

Time series were produced for the normalized difference indices (vegetation, soil, and water–NDVI, NDSI, and NDWI) for both MODIS and Landsat 5 and 7, referred to as the Normalized Difference Index transformation [4]. The MODIS indices are 250 m (NDVI) and 500 m (NDWI and NDSI), and the Landsat indices are 30 m resolution. While the higher spatial resolution of

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Landsat is optimal for mapping stationary or slowly changing landscapes, the daily temporal resolution of MODIS is optimal for mapping highly non-stationary landscapes, such as the estuarine ecosystem.

Examples of the MODIS indices are shown for two locations in Fig. 1 and Fig 2. Each figure shows the NDSI (soil), NDVI (vegetation), and NDWI (water) index as a function of day number for 2005. The figures represent two of the monitoring stations in the Calcasieu-Sabine (CS) Basin, CS20-07 and CS20-15R, located in the area of Mud Lake in the southeastern corner of the study area (see Fig. 3). The peak in the NDWI occurs on the day of Hurricane Rita, September 24, 2005. In most of these profiles, the increase in the water index is accompanied by a decrease in the vegetation index and a period of declining water. The soil index also represents non-green or dead vegetation and often appears on a rise after the hurricane's destruction of the marsh vegetation. The behavior of these indices over time is indicative of which areas remain flooded, which areas recover to their former levels of vegetative vigor, and which areas are stressed or in transition.

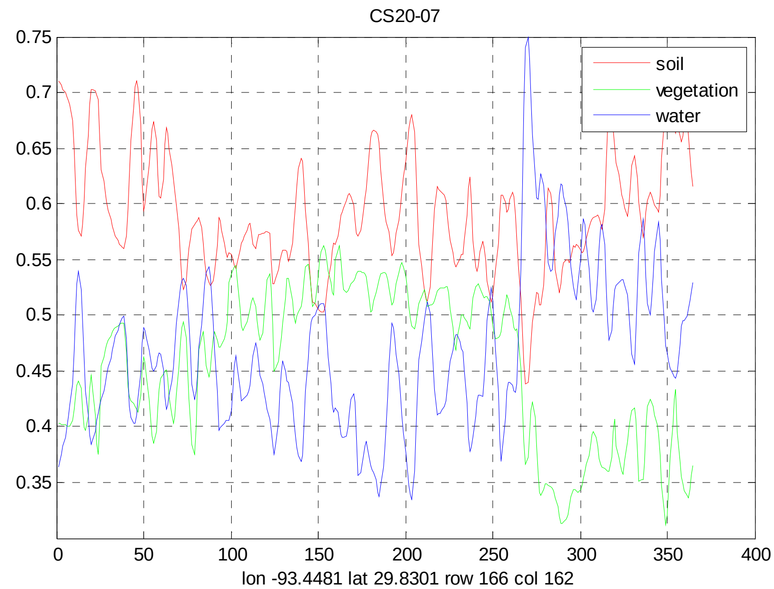

Fig. 1 MODIS-derived normalized difference indices for soil, vegetation, and water plotted against days 1-365 of 2005. The peak in the water index occurs at the time of Hurricane Rita (Sept. 24, 2005). The decline in the vegetation index is due to the destruction of live marsh vegetation. The soil index, which also represents non-green vegetation and non-water areas, increases as the water goes down.

While the MODIS indices contain valuable information for habitat monitoring over time, their spatial resolution makes it difficult to verify and assess the derived information in a marsh ecosystem. Landsat-derived indices deliver much improved resolution. One of the goals of this project is to map persistent flooding, and we have succeeded in doing so using the MODIS and Landsat indices. The indices are plotted over time and a baseline is selected for average water levels given a pre-Hurricane series. As an example, the NDWI is used to assess flooding in 2004, prior to Hurricane Rita. For the MODIS NDWI, a threshold value is selected representing normal water levels of the index. The number of days the pixel's NDWI exceeds the threshold is used to calculate the percent inundation. Inundation levels are mapped in 10 percent increments as shown in Fig. 4 where Landsat-derived NDWI time series are used. The Landsat time series are derived by interleaving Landsat 5 and Landsat 7 imagery to produce a weekly time series of each index. The percent inundation is therefore based on only one reading per week, whereas the MODIS percent inundation is based

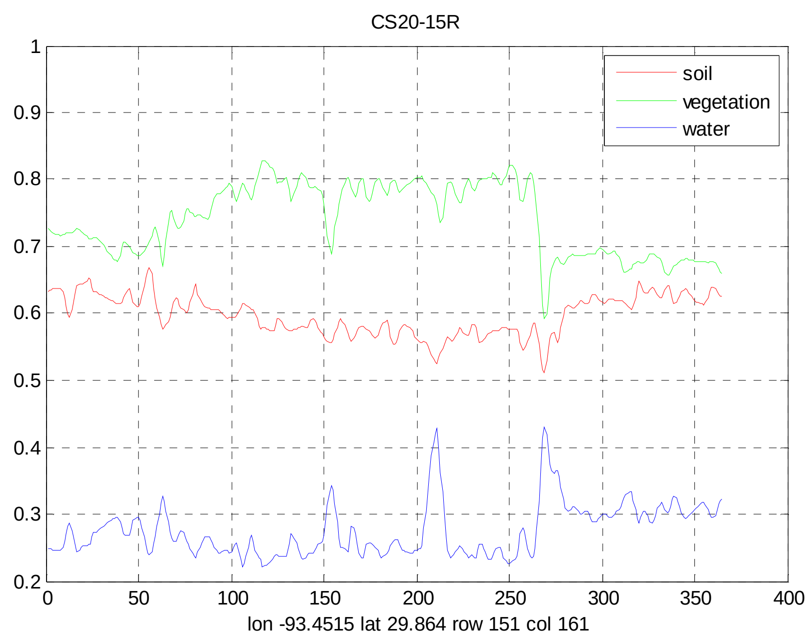

Fig. 2 This station shows a predominance of green vegetation, which is impacted severely by the hurricane and rising water. Although the water recedes, the index remains higher than normal, indicating that the area may have remained flooded. An increase in the soil index suggests an increase in non-green vegetation although it approaches levels similar to the beginning of the year.

on daily values of the 500 m NDWI shown in Fig. 5. Clearly, the 500 m resolution is too coarse for some areas where more detail is needed. Similar estimates were made using the NDVI derived from MODIS, which is a 250 m product, and an effort is being made to produce the NDWI at 250 m since it the result of a 250 m band and a 500 m band difference.

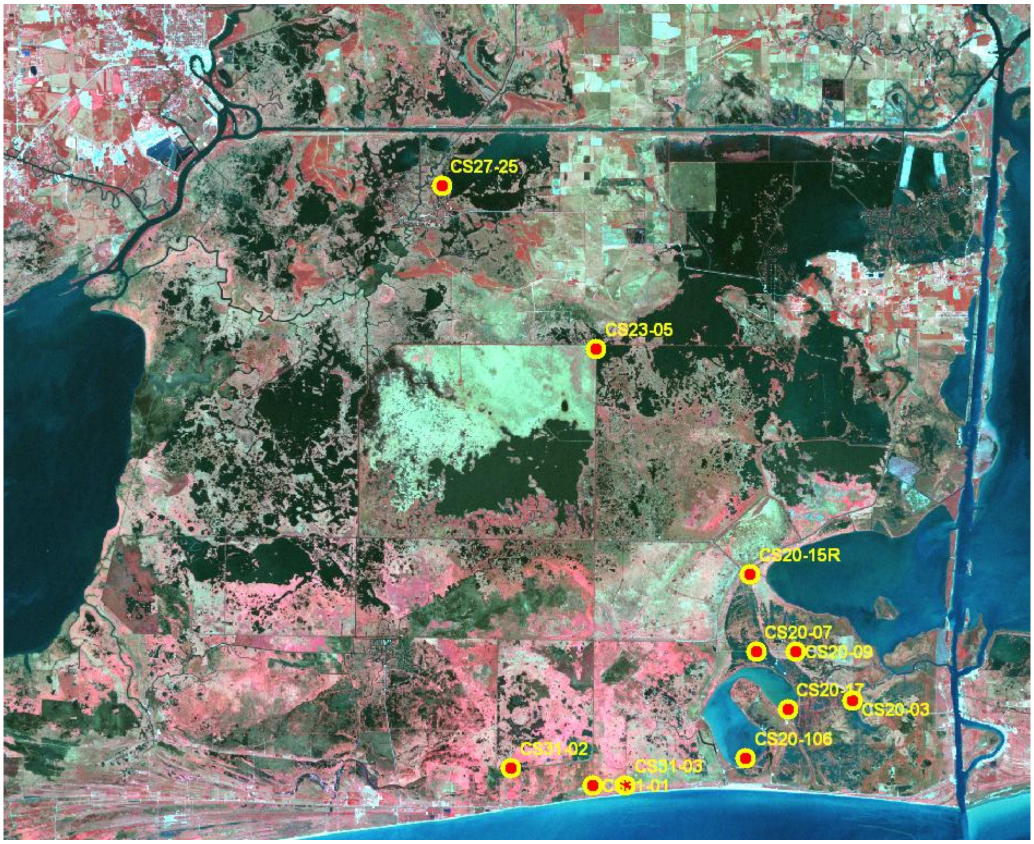

Fig. 3 The Calcasieu-Sabine Basin study area comprises the area between Lake Calcasieu and Sabine Lake (east and west), and between the intracoastal waterway and the Gulf of Mexico (north and south).

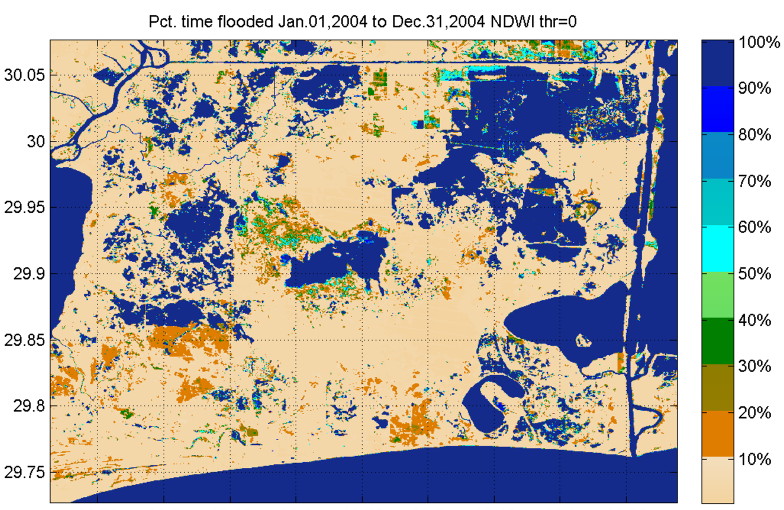

Fig. 4 Landsat-derived NDWI is used to map percent inundation based on weekly observations in the Calcasieu-Sabine Basin for the year 2004.

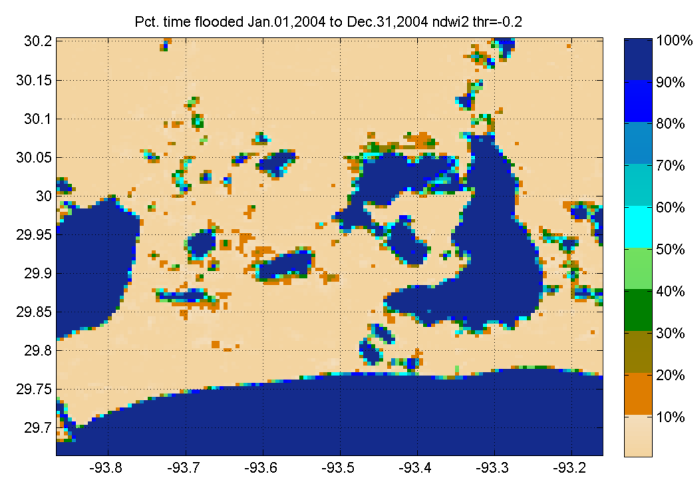

Fig. 5 MODIS-derived NDWI at 500 m resolution is used to map percent inundation based on daily observations for 2004.

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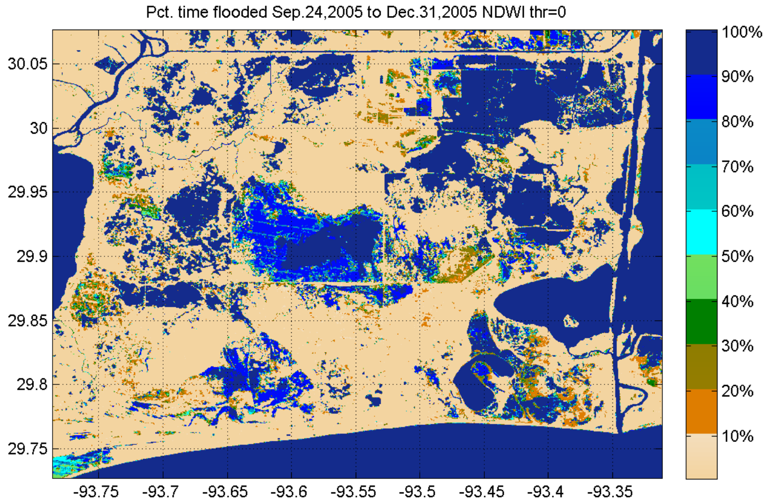

Fig. 6 Flooding persistence after Hurricane Rita during the fall of 2005.

Flooding in 2005 after Hurricane Rita is in Fig. 6. Floodwaters persisted in many areas previously not under water for great periods time when compared to the 2004 inundation There was below-average rainfall during this [5], indicating that the water was left behind the storm.

III. RESULTS

Assessment of floodwater persistence estimates have been attempted using water elevation levels measured at CRMS and CS monitoring stations in the study area. Some these stations have continuous data with gaps, none had continuous data over the study from 2004 to 2006. Where there were continuous readings, the water level was assumed constant around the station and was compared to a Digital Elevation Model (DEM) developed from Louisiana lidar data acquired for the Federal Emergency Management Agency in February 2003 [6]. The DEM has a spatial resolution of 5 meters and vertical resolution of 0.01 feet . Fig. 7 shows a time series of flood maps illustrating how the Mud Lake area was inundated by Hurricane Rita and how the flood waters lingered for several months. This illustration was produced by flooding the terrain to the levels recorded at a CRMS station in the area. We attempted to improve the analysis by utilizing data from all available field stations across the study area on any given day. However, there was insufficient data to interpolate a water-level surface to flood the DEM in a more realistic way because several monitoring stations were destroyed or inoperable after the storm.

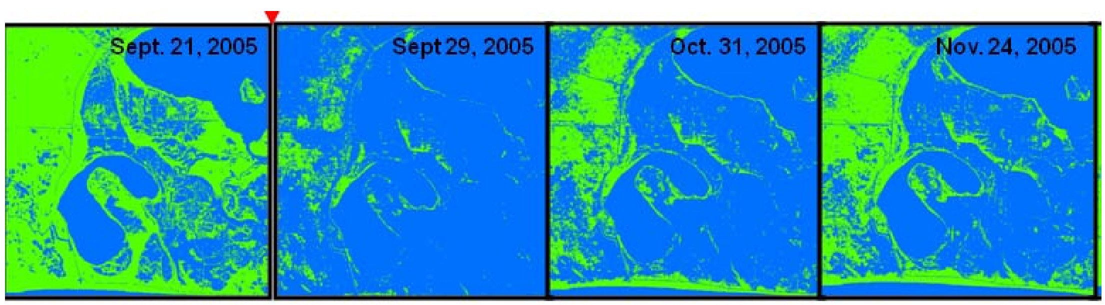

Fig. 7 Flood simulation derived from water level measurements compared to digital elevation model.

Preliminary results show somewhat good agreement between the simulated flood maps and the Landsat and MODIS flood maps (Fig. 8); however, more work is needed in assessing the relative extent of floodwaters given the water levels and marsh surface elevations relative to the NAVD88 vertical datum. Future work includes comparison to radar-derived flood maps and calibration of water level measurements.

The flood persistence maps will be used with a salinity product to derive persistent saltwater flood maps. Several efforts have been made to map salinity with multispectral and hyperspectral data; however, results to date are inconclusive. An interim salinity product has been created using CRMS and CS monitoring station data and krigging. The salinity data were somewhat sparse, so salinity maps were made using data over 3-month periods, or quarters. An example of one of these salinity maps is shown in Fig. 9 where higher than average salinity values were measured and mapped due to the high-salinity flood waters and low precipitation during the months following the hurricane. A precipitation record from the area is shown in Fig. 10 where the below average rainfall in the spring contributed to the high salinity levels seen in the basin. The salinity product will be combined with the inundation product to produce saltwater inundation maps.

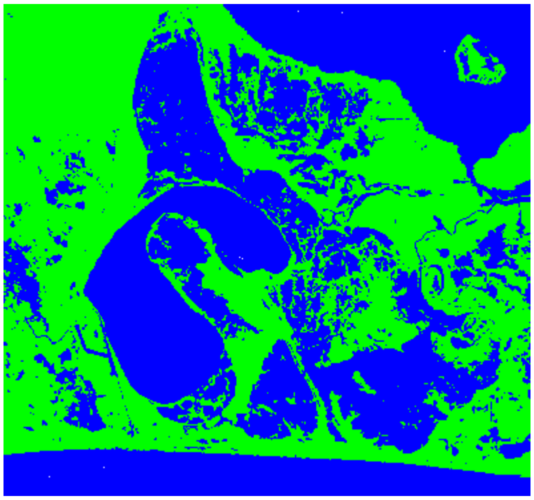

Fig. 8 Flood map derived from Landsat NDWI for Oct.31, 2005 shows some agreement with the simulated flood map; however, the simulation has not been corrected to marsh elevation relative to the NAVD88 datum.

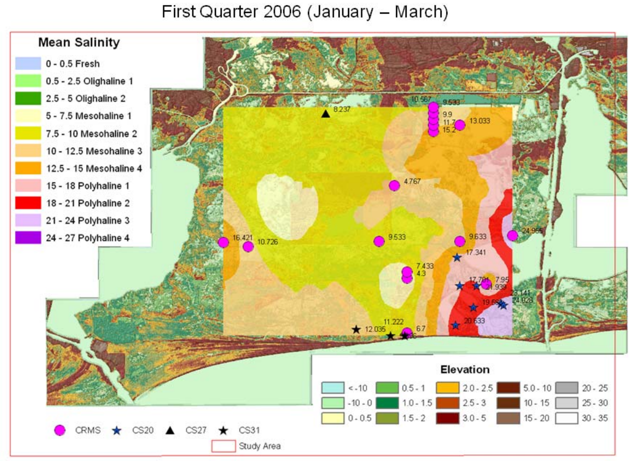

Fig. 9 Salinity estimates from kriging of salinity measurements made at CRMSs during the first quarter of 2006 show high salinity values resulting from persistence of saline floodwaters and below average precipitation.

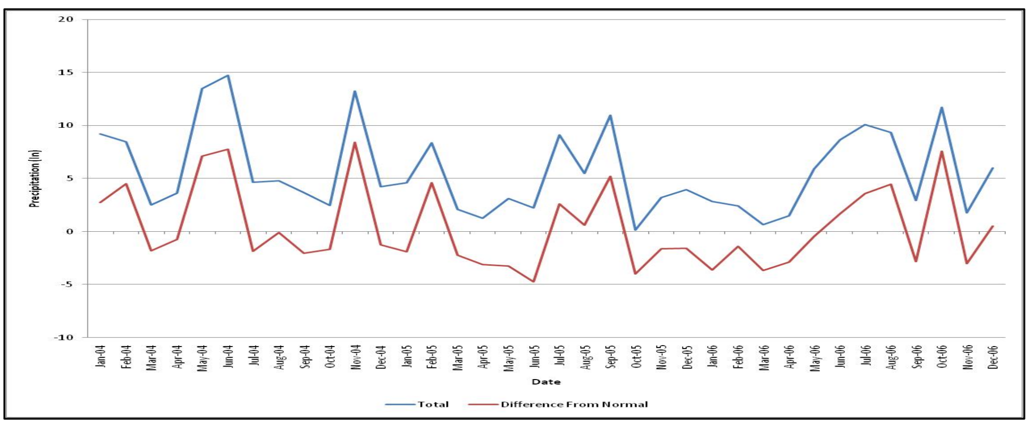

Fig. 10 Monthly Precipitation Data 2004 – 2006[5].

IV. SUMMARY

The work and results to date have shown good concurrence with ground truth and land use changes in the study area. Current work is focused on improving the temporal resolution of Landsat using MODIS and/or improving the spatial resolution of MODIS using Landsat. Preliminary results of using an adaptive technique to model Landsat/MODIS intermediate products show promising results and will be investigated in a follow-on project. Improved methods for validation are also being coordinated and developed.

These products may identify areas that experience variable flooding and salinity regimes and, consequently, may be more vulnerable to the loss of habitat and environmental degradation. Habitat models will aid in assessing, monitoring, and restoring the health of coastal estuaries to ensure that they will continue to provide coastal residents with incalculable economic benefits, such as providing a buffer against storm surge, filtering pollutants, and providing a spawning ground for marine life.

V. ACKNOWLEDGEMENTS

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